Sensor Technology-State of the Science

Ron Williams

On Behalf of the EM-3 Team

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July 2014

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ORD EM-3 Efforts (2012-2014)

FY12

- ASAP workshop
- Sensors Evaluation and Collaboration

FY13

- Regions workshop
- Short-term sensor field tests (DISCOVER-AQ, AIRS, roadside, wildfire, fenceline)
- Data visualization support: RETIGO
- Designing/building autonomous systems: Village Green Project

FY14

- Air sensors workshop
- Citizen Science Toolkit (R2 RARE)
- Short-term sensor field tests (DISCOVER-AQ, AIRS, roadside, wildfire, fenceline)
- Sensor network intelligent emissions locator tool (SENTINEL)
- Designing/building autonomous systems: Village Green Project II,
- Long-term testing of sensors: Regional Methods Project
- Data visualization support: RETIGO

Workshops

Performance testing

Sensor system build

Sensor data tools

Goals of the ACE EM-3 Research Agenda

1. Investigate emerging technologies and their potential to meet future air quality monitoring needs for the Agency as well as other partners/stakeholders

2. Establish market surveys of commercially-available air quality sensors

3. Conduct an extensive literature survey describing the state of sensor technologies

4. Develop sensor user guides

5. Educate sensor developers/sensors users on the state of low cost censors

6. Facilitate knowledge transfer to Federal/Regional/State air quality associates

7. Work directly with sensor developers to dramatically speed up the development of next generation air monitoring

8. Support ORD's Sensor Roadmap by focusing on areas of highest priority (NAAQS, Air Toxics, Citizen Science)

9. Establish highly integrated research efforts across ORD and its partners (internal/external) to ensure consistent

Investigating Emerging Technologies

- Understand the need/reason for this rapidly expanding market
- Conduct market surveys
- Conduct extensive laboratory and field evaluations of the most promising technologies (examples : MCRADAs, DISCOVER-AQ, Village Green Project)

A Typical Regulatory Monitor

•Produces data of known value and highly reliable
•Stationary- cannot be easily relocated
•Instruments are often large and require a building to support their operation
•Expensive to purchase and operate (typically > $20K each)
•Requires frequent visits by highly trained staff to check on their operation
•Often operate for 10+ years before needing to be replaced

A Typical Low Cost Monitor

•Inexpensive ($100 to $5000) to purchase
•Highly portable and easy to operate (often mobile)
•Requires little or no training to start collecting data
•Inexpensive to operate (replace or recharge batteries)
•Lifetime of service not expected to exceed 1-2 years

High interest by public for more information

Public demand for more personalized information – what about *my* exposure, *my* neighborhood, my family

What are some of these new technologies?

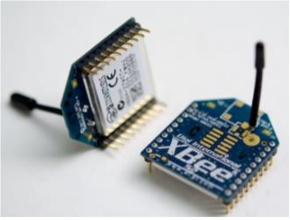
Smartphone / Tablet in widespread use

e.g., fitbit activity tracker

Miniaturized environmental sensors

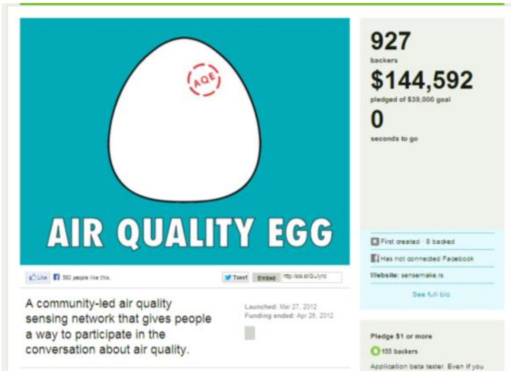
Introduction of low cost controls and communications

e.g., Arduino microprocessor



Crowd-funding supporting do-it-yourself (DIY) innovation

e.g., Kickstarter



Web-based portals are being developed

Emerging data-viewing/communication apps

airalliancehouston.org

londonair.org.uk/ iphone

aircasting.org

AirCasting App

AirCasting Air Monitor

airqualityegg.com

Intensive Literature and Market Surveys

EPA/600/R-14/051

RESEARCH AND DEVELOPMENT HIGHLIGHTS:

MOBILE SENSORS AND APPLICATIONS FOR AIR POLLUTANTS

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31 October 2013

http://www.epa.gov/research/airscience/next-generation-air-measuring.htm

Disclaimer

- Mention of trade names or commercial products does not constitute endorsement or recommendation for use and are provided here solely for informational purposes as to some of the market survey information being gathered

Example-Sensaris

Sensor gathers data and send it to the phone via Bluetooth

Real time data displayed on phone and broadcast data to the web

Get charts, track data and manage sensors from one web interface

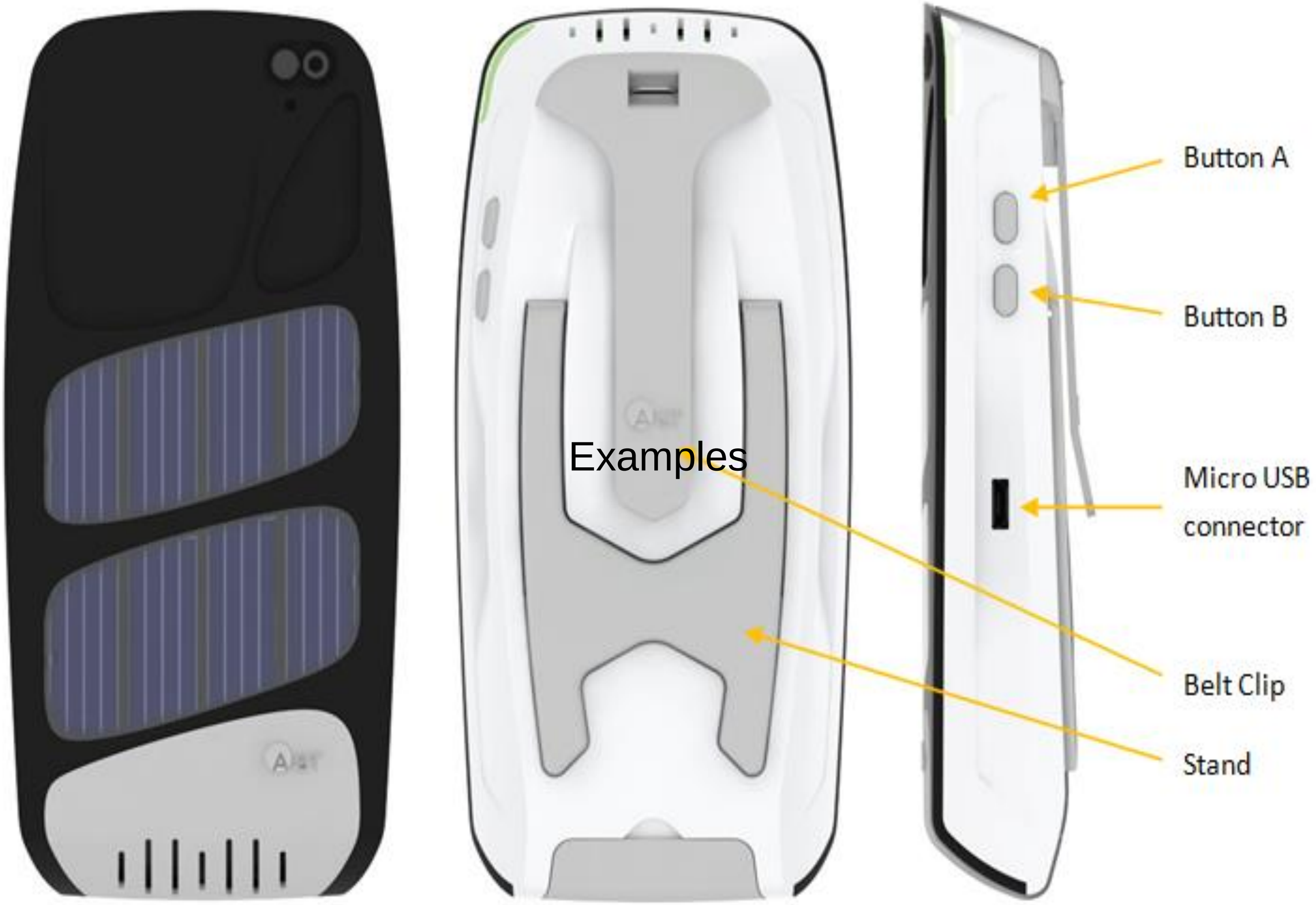
Example-Sensaris PM

Example-AirCasting

AirCasting App

AirCasting Air Monitor

Example-AGT


Examples
Button A
Button B
Micro USB
connector
Belt Clip
Stand

Example-CanAiriT

Example-Cairpol PM

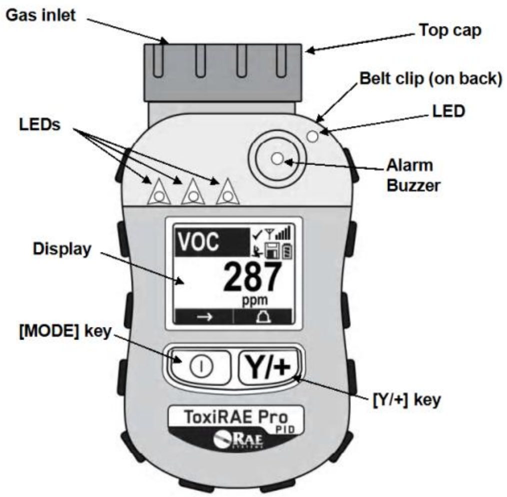
Example-Carnegie Mellon (Speck)

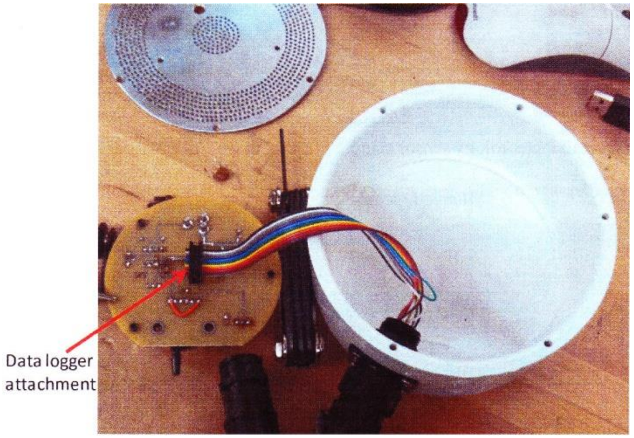
Example-Dylos

Example-Met One

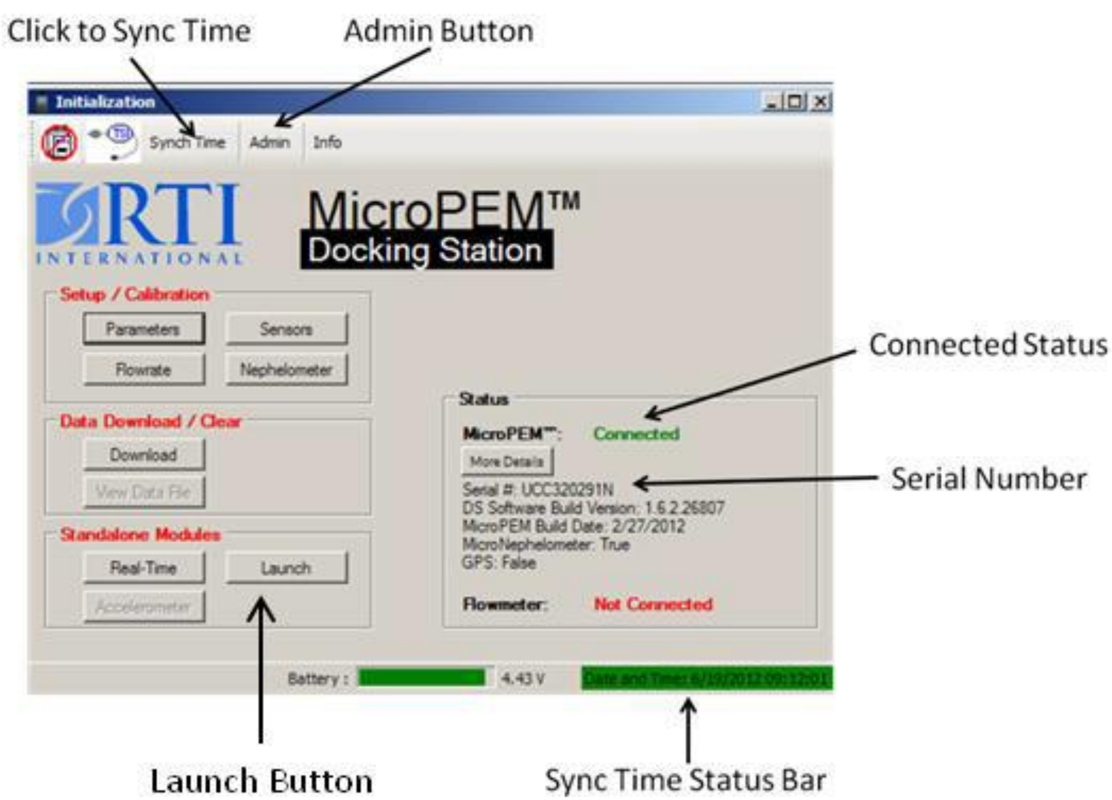
Example-Cairpol (VOC,NO_2,O_3)

Example-UniTec, ToxRae, EPA VOC sensors

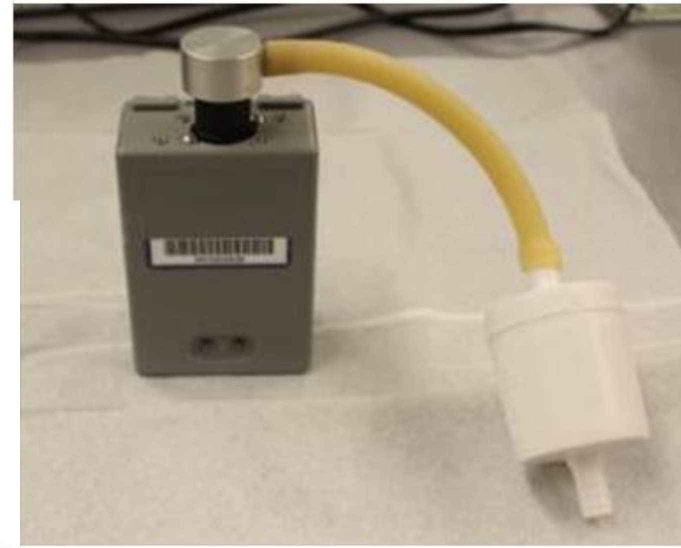




Example-RTI MicroPEM



Zero Cap on MicroPEM



Example-AQ Mesh

Release of the Citizen Science Fact Sheet

Defines roles of low cost sensors for citizen science

EPA

www.epa.gov/research

science in ACTION

INNOVATIVE RESEARCH FOR A SUSTAINABLE FUTURE

CITIZEN SCIENCE OPPORTUNITIES FOR MONITORING AIR QUALITY

What is Citizen Science?

Citizen science includes projects and programs designed to engage the public in scientific investigations, such as asking questions, collecting data or interpreting results. Citizen science includes volunteer monitoring, public participation in scientific research, and many other activities.

The U.S. Environmental Protection Agency fosters citizen science in a number of ways. The Agency creates citizen science projects, participates in projects managed by other organizations and helps individuals identify and develop citizen science projects for the public.

Citizen Science and Air Quality Monitoring

Air quality in the United States is tracked using a network of national monitors located across the country. The monitors use established technologies that provide accurate regional data on air quality for use in implementing the nation's air quality standards, enforcement and research.

The monitoring network, however, does not always lend itself for use by citizens because it is designed to provide regional data, and has limited utility for direct personal or local air quality information. The monitoring systems are also large and stationary, expensive to operate and require frequent maintenance by trained staff.

Citizens are interested in learning more about local air quality where they live, work and play. New technologies are being developed and evaluated to fill this need through EPA's Next Generation Air Monitoring research activities.

Equipment at a typical regulatory monitoring site.

A wide variety of small, portable and lower-cost monitoring devices are being developed by industry, universities and individuals to potentially enhance air quality monitoring capabilities in the future. EPA scientists are collaborating with other federal, state and non-governmental institutions to encourage the development of new sensor and app technologies for measuring air quality and are evaluating the performance of these new technologies. Such technologies are not yet approved for regulatory monitoring.

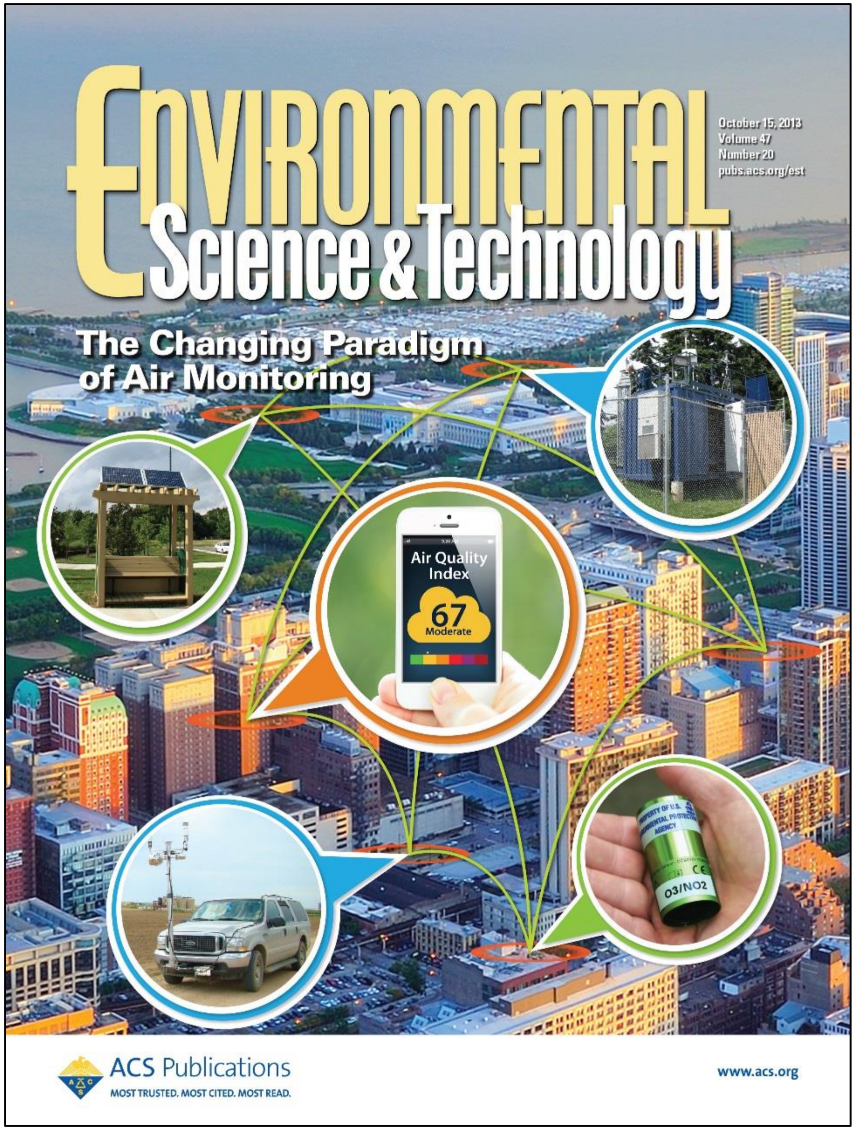
The next generation air monitors are:

- Inexpensive ($100 to $5,000)
- Highly portable and easy to operate (often mobile)
- Require minimal training to start collecting data
- Inexpensive to operate (replace or recharge batteries)

1 U.S. Environmental Protection Agency
Office of Research and Development

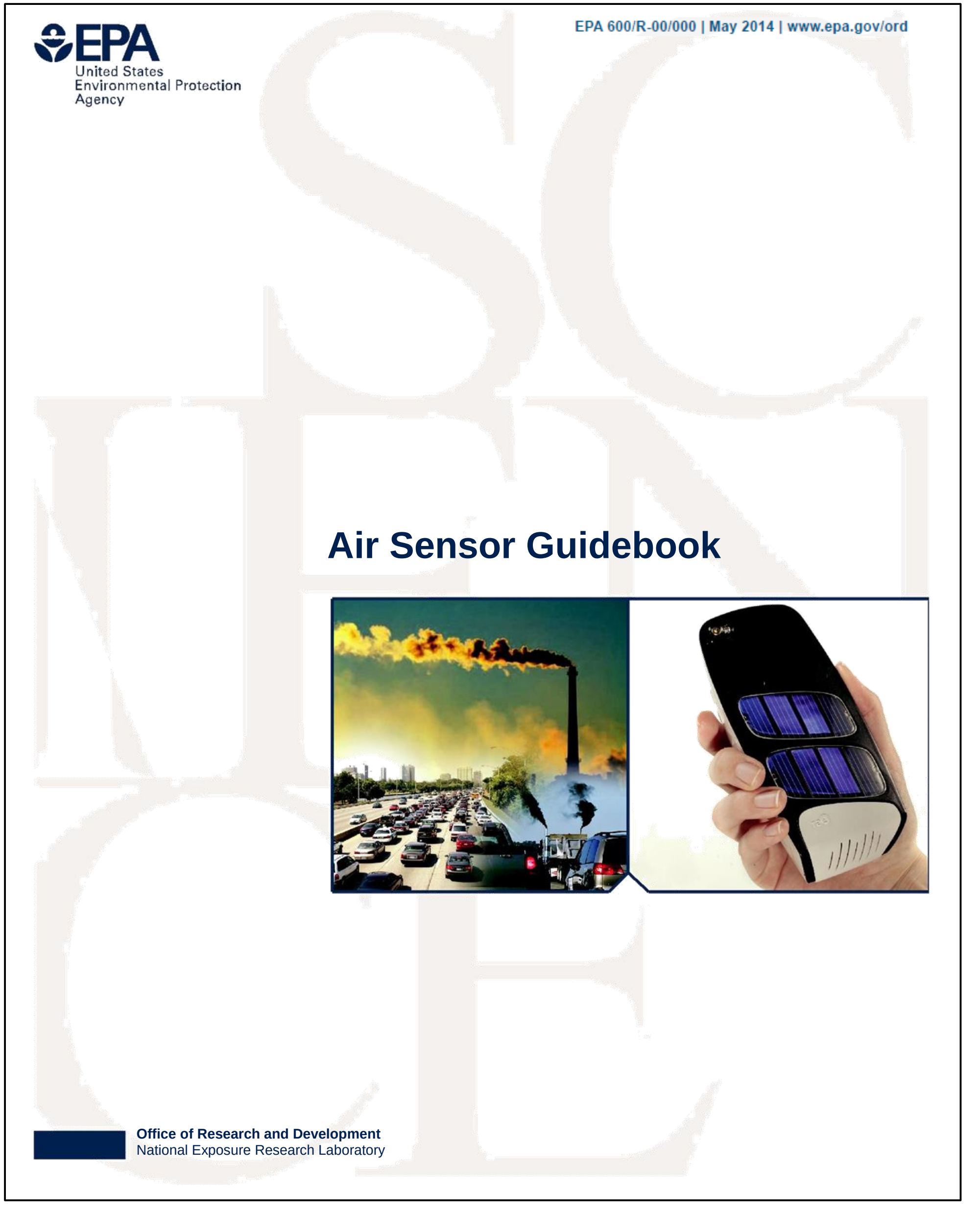
http://www.epa.gov/research/airscience/next-generation-air-measuring.htm

Critical Peer Reviewed Articles Defining Emerging Sensor Technology



Development of the Air Sensors Guidebook

Defines what sensor users need to understand if they are to collect meaningful air quality data



http://www.epa.gov/research/airscience/next-generation-air-measuring.htm

Providing Citizen Scientists A Direct Means of Sensor Data Comparison

Sensor Evaluation API

Log Out

- Home
- Web Services

AirNow Sensor Evaluation API - Web Services

By Site Documentation Query Tool

This web service provides access to high-time-resolution air quality data collected by U.S. state and local air quality agencies. This web service takes various input parameters (site, parameter, duration, parameter occurrence code, date ranges, and output format) specified in the URL and returns data in CSV, JSON, or XML format.

http://smallsensors.sonomatechdata.com/webservices

Sensor Evaluation MCRADAs

www.epa.gov/airscience

AIR CLIMATE & ENERGY RESEARCH PROGRAM
BUILDING A SCIENTIFIC FOUNDATION FOR SOUND ENVIRONMENTAL DECISIONS

Sensor and Apps Evaluation Opportunity

WHAT: EPA offers technology developers the opportunity to send in your sensor for evaluation in a controlled laboratory setting.

WHEN: Nominate your device by June 30, 2012
Testing to occur July – September, 2012

HOW: Device developers should submit a statement of interest to EPA by June 30, 2012 providing basic information about their device. Due to capacity constraints, EPA will accept a limited number (~10) devices for evaluation over a range of pollutant concentrations and environmental conditions (e.g. humidity and potential interferences). Participants will be invited to visit the EPA lab in early July to discuss their instruments, the evaluation protocol, and receive a tour of the facility. Following the completion of the evaluation each participant will receive information on the performance of their device under known environmental conditions.

QUESTIONS or Point of Contact: Ron Williams, 919-541-2957, williams.ronald@epa.gov

SELECTION CRITERIA: Devices receiving the highest consideration:

- have the technical feasibility to measure NO_2 and/or O_3 at environmentally relevant concentrations,
- have some preliminary data on expected performance characteristics,
- have not previously undergone standardized evaluations under known challenge test conditions by any party, and
- represent highly portable sensor and smart phone type applications featuring continuous measurement capabilities.

Description:

- Open call for potential collaboration
- O_3 and NO_2 focus
- A total of 9 research groups nominated devices for evaluation
- Variety of devices
- Formal cooperative agreements established
- Not FRM/FEM Evaluations

Feedback Provided to Sensor Developers:

- General performance of the device
- Observations on operation
- Validated non-summarized data
- EPA's intent was not to compare one specific device with another
- EPA recognized the confidential nature of the technologies being evaluated

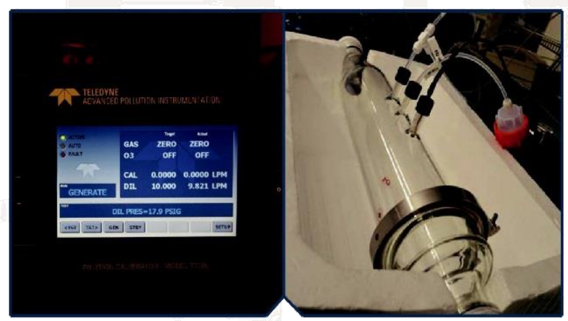
http://www.epa.gov/research/airscience/next-generation-air-measuring.htm

MCRADA Evaluation of NO_2 and O_3 Sensor

EPA United States Environmental Protection Agency

EPA 600/R-00/000 | May 2014 | www.epa.gov/ord

Sensor Evaluation Report



Office of Research and Development
National Exposure Research Laboratory

Technical Aspects – FRM/FEM Performance Parameters

40 CFR Part 53 Table B-1: Performance Limit Specifications for Automated Methods

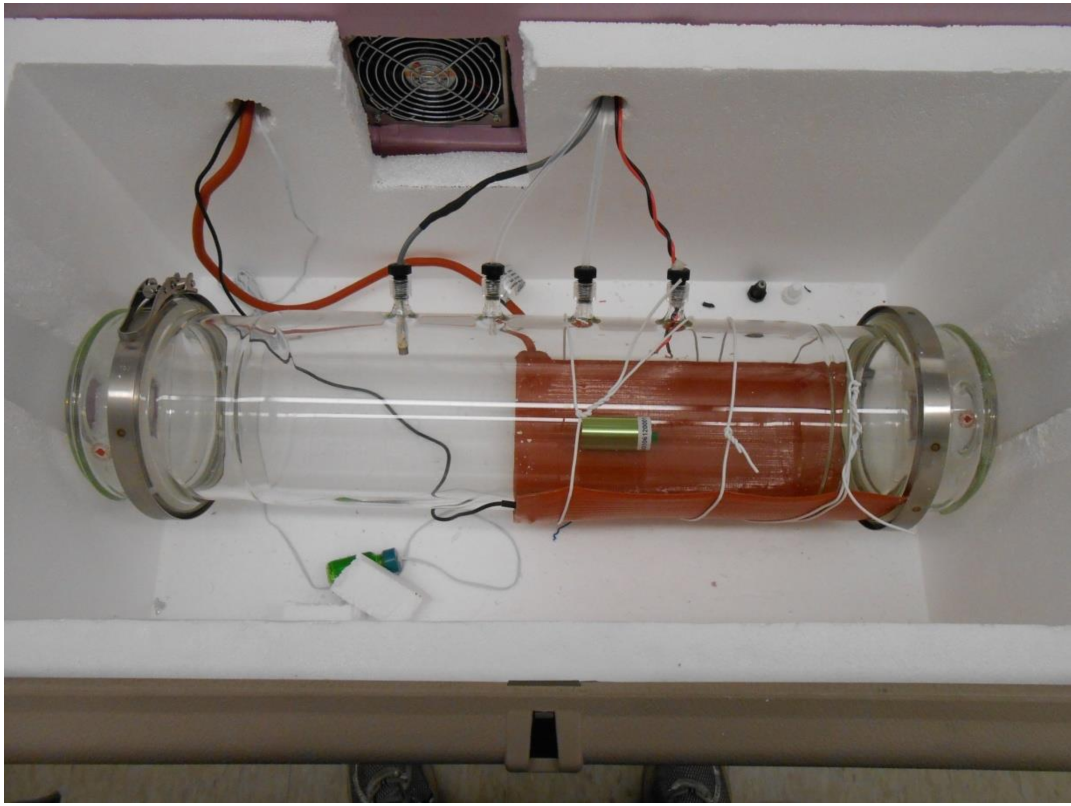
Performance parameter	Units[1]	SO_2 Std. range[3]	SO_2 Lower range[2,3]	O_3 (Std. range)	NO_2 (Std. range)
1. Range	ppm	0-0.5	<0.5	0-0.5	0-0.5
2. Noise	ppm	0.001	0.0005	0.005	0.005
3. Lower detectable limit	ppm	0.002	0.001	0.010	0.010
4. Interference equivalent					
Each interferent	ppm	±0.005	[4]±0.005	±0.02	±0.02
Total, all interferents	ppm	---	---	0.06	0.04
5. Zero drift, 12 and 24 hour	ppm	±0.004	±0.002	±0.02	±0.02
6. Span drift, 24 hour					
20% of upper range limit	Percent	---	---	±20.0	±20.0
80% of upper range limit	Percent	±3.0	±3.0	±5.0	±5.0
7. Lag time	Minutes	2	2	20	20
8. Rise time	Minutes	2	2	15	15
9. Fall time	Minutes	2	2	15	15
10. Precision					
20 % of upper range limit	ppm	---	---	0.010	0.020
	Percent	2	2	---	---
80 % of upper range limit	ppm	---	---	0.010	0.030
	Percent	2	2	---	---

Evaluation Aspects – Performance Traits

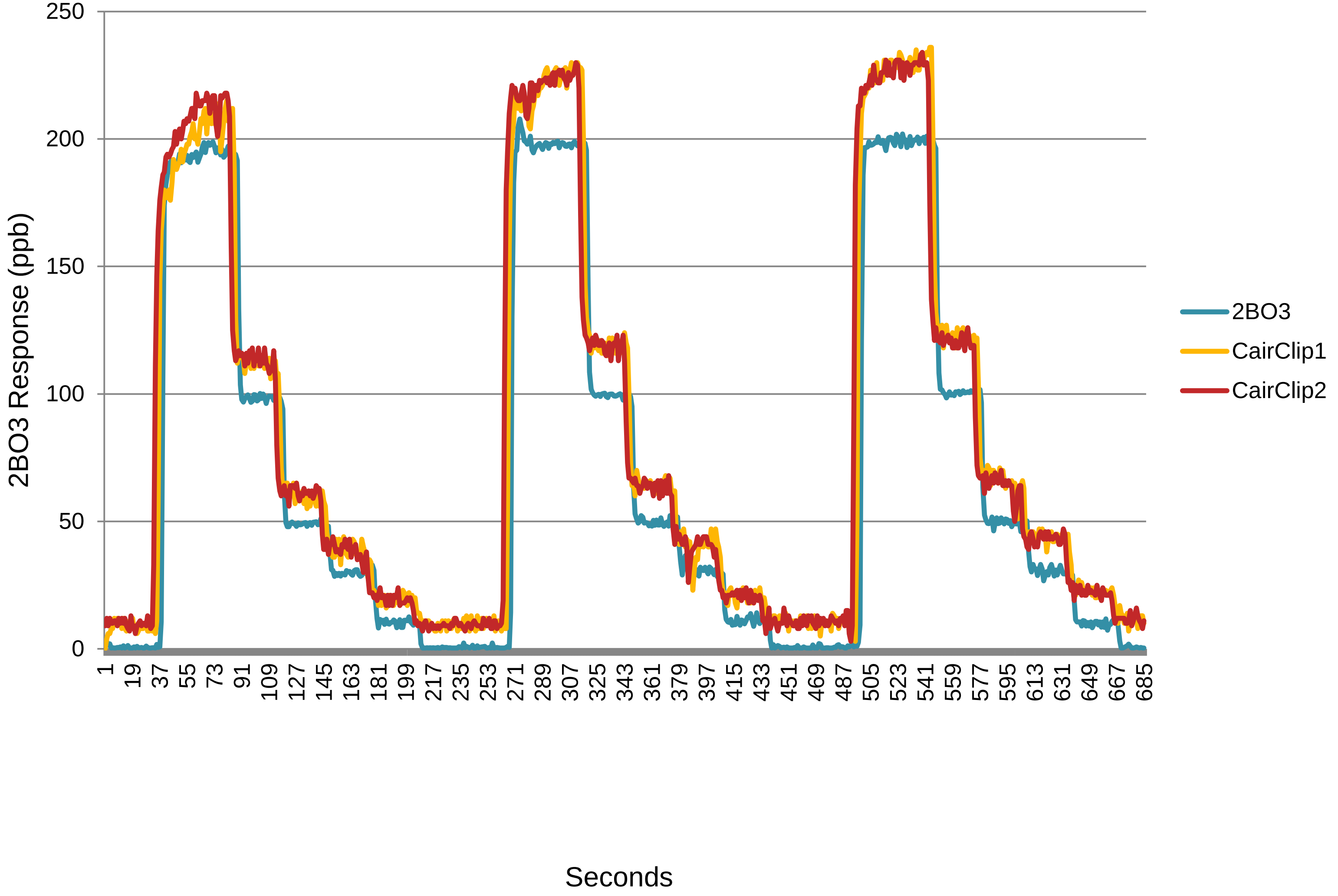
1. Linearity (range)
2. Precision of measurements
3. Lower detectable limit
4. Resolution (noise)
5. Response time (lag and rise time)
6. RH and temperature influence
7. Interference equivalent

Sensor performance evaluation: lab investigations

Example: Cairpol sensor for NO_2/O_3



Example of Basic Performance Characteristics



Typical O_3 and NO_2 Sensor Performance Characteristics

	Conditions	Response	Linearity	Precision	LDL	IDL	Res low	Res High	Lag Time	Rise Time	SO2 int	O3 Int	NO2 Int
		kOhm/ppb	R^2	ppb	ppb	ppb	ppb	ppb	minutes	minutes	ppb	ppb	ppb
O3	Normal	0.4186	0.9824	10.3	15.6	11.8	8.3	14.1	1	5	7.5	NA	32.2
	Hot	0.2492	0.9933	13.6	12.4	18.1	6.8	37.7	1	6	Widely Variable		
	Humid	0.3383	0.9774	2.6	12.4	16	5.9	4	1	4			
	Cold	0.5484	0.9772	7.2	9.8	11.3	2.6	6.1	1	3			
NO2	Normal	0.6362	0.9972	1.2	15	9.5	1.8	2.3	1	5	19.5	off scale	NA
	Hot	0.0995	0.9919	6.4	13.6	24	5.7	8.1	1	20	Widely Variable		
	Humid	0.4526	0.9937	7.4	17.7	22.8	2.7	5.2	1	7			
	Cold	3.4208	0.9917	7.5	10.2	5.2	0.8	6.8	1	6			
CFR O3	NA	NA	NA	10	10	10	5	5	20	15	20	20	20
CFR NO2	NA	NA	NA	10	10	10	5	5	20	15	20	20	20

Sensor and Data Quality-Considerations

- Weather. Many devices are temperature and relative humidity (RH) sensitive
  - Sensors often function poorly in high humidity
  - Sensors often respond differently when it is either very hot or very cold (may under or over-report true pollutant concentrations or even stop working)
  - The impact on data quality for temperature and RH effects for many low cost sensors have not been established

Unique Qualities

- Battery life. It is apparent that a wide range of battery options are being used. Operating periods from 3 hrs to 24 hrs have been observed
- Recharge issues. Very specific recharge requirements (USB to use of transformed outlet voltage) and recharge times
- Orientation. Some devices had to have a very specific orientation in the exposure chamber

Unique Qualities

- Sensor Interface. Some of the sensors required a discreet movement of air flow over the surface of the sensor. (Goldilocks requirement= not too much, not too little). Interface stagnation versus physical influence (cooling of sensor influences resistance and therefore output had to be considered individually for each sensor.
- Test range. There appears to be a wide range in sensor sensitivities

Communication Protocols

- WiFi, Bluetooth, hard line (direct interface with laptop, tablet or other device), flash drive download, on-screen
- Communication protocols were often less than foolproof and work around solutions had to be developed. Internal wireless security issues, cell-based signal strength and other factors had to be resolved (all were resolved)

Data Recovery/Processing

- Raw data processing (even reporting in some cases) often required interface with proprietary software data management programs. Such links prevented direct access to raw data and represented another communications linkage that had to be resolved
- Difficultly in some situations to get to raw data as the raw signal was processed via developer's software prior to being "reported" back to user

Field Evaluations

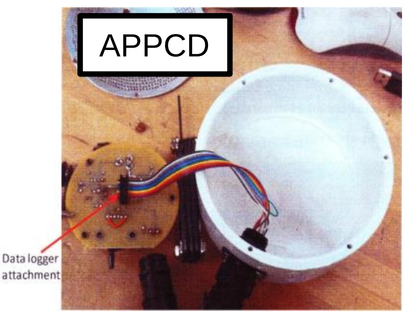
- PM and VOC Sensors (Research Triangle Park)
- DISCOVER AQ (Houston)
- Village Green Project

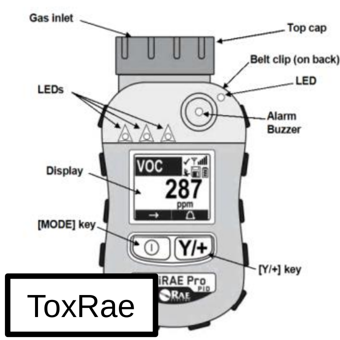
Low Cost VOC Sensor Characterization at Near Road Site

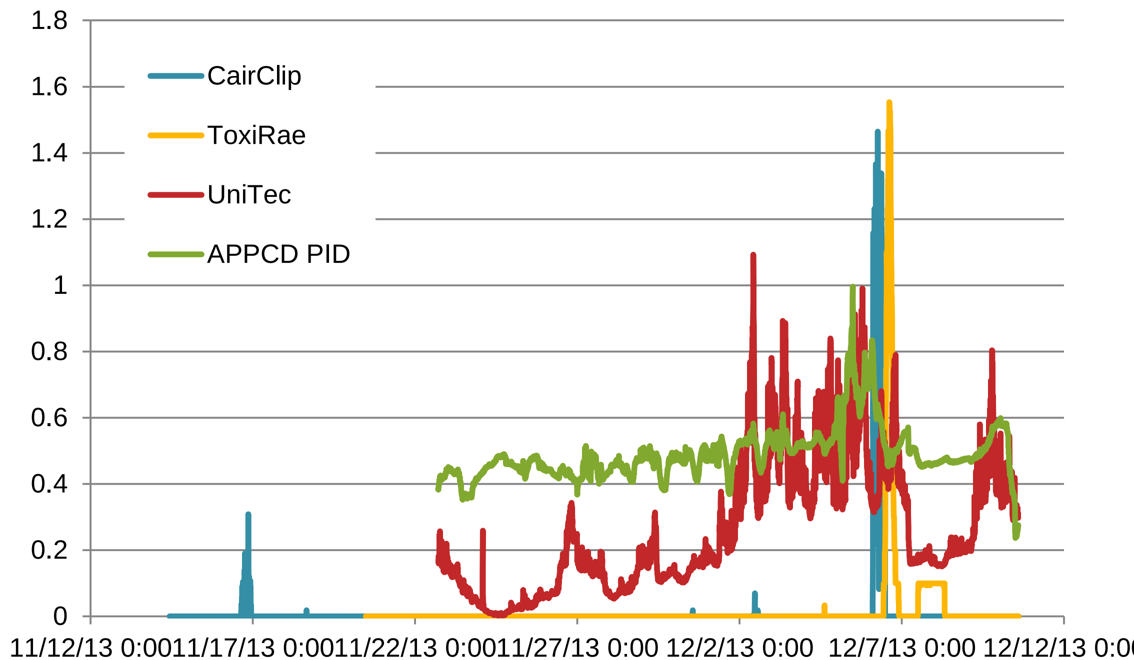
Sensor performance evaluation: lab and field

VOC sensors

- It is obvious the sensors have a wide range of sensitivities.
- Specificity is currently being determined on select models.







Preliminary Performance Characteristics of VOC Sensors

Sensor	R^2 Temp Linearity (°C)	R^2 RH Linearity	Time Resolution (s)
AirBase CanarIT (ppb)	0.4942	0.4087	20
APPCD PID (V)	0.0811	0.2191	1
CairClip (ppb)	0.0038	0.0307	60
Sensotran Benzene (V)	NA	NA	600
ToxiRAE Pro PID (ppm)	0.0088	0.3597	20
UniTec Sens-It (V)	0.0327	0.0079	60

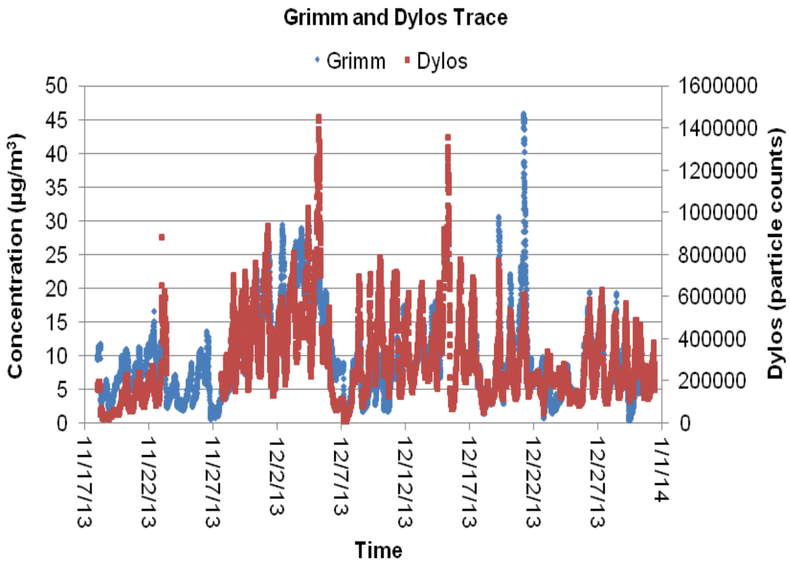
Direct Collocation with FEMs

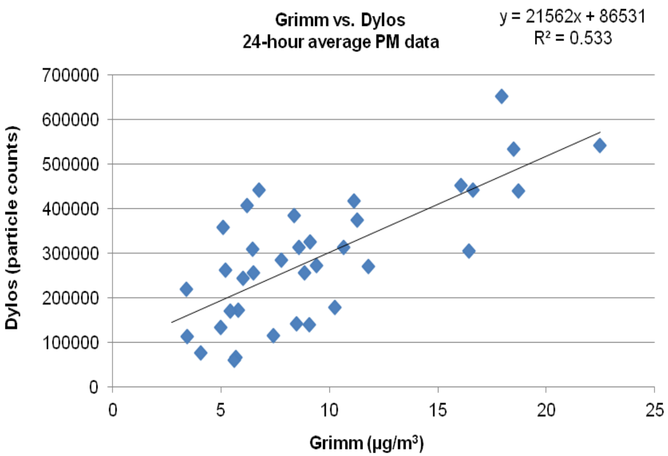
Sensor performance evaluation: lab and field

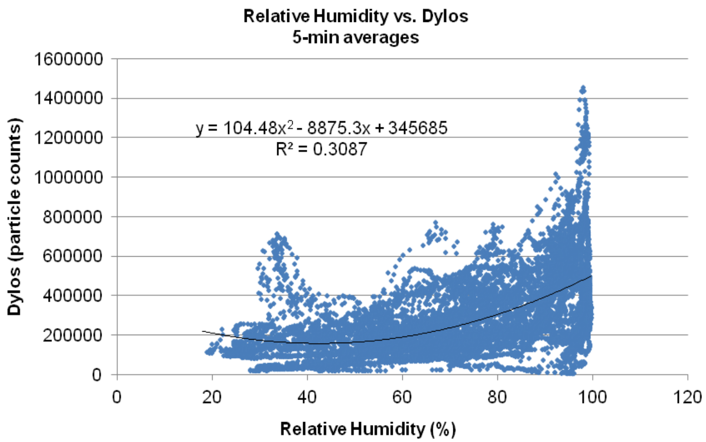
PM short-term tests – ambient, field conditions

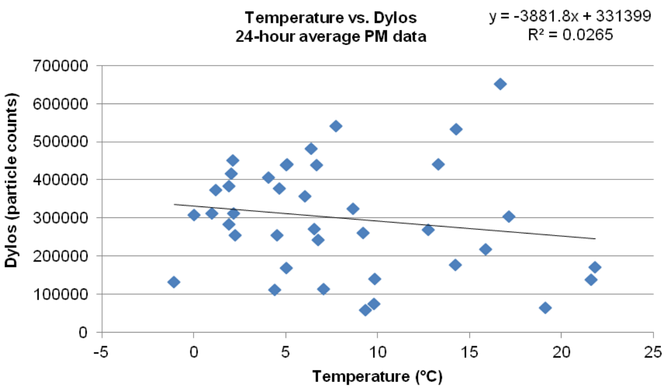
- Most low cost PM sensors provide on **modest agreement with FEM** in direct collocation challenge (CODs between 0.1 to 0.5).
- **Temperature and RH being observed as influencing factors**. Some (Cairpol) suffering from very poor sensitivity. The Dylos appears to be one of the more agreeable units even though it only provides particle counts (not mass).
- We have no information on intra/inter-variability of these sensors.

An Example of In-Depth PM Sensor Evaluation









Low Cost PM Sensor Evaluations

Sensor	FEM R^2 Linearity	RH Limit	Temp R^2 Linearity	Time Resolution
AirBase CanarIT ($\mu g/m^3$)	0.004	100%	None	20 s
CairClip PM ($\mu g/m^3$)	0.064	95%	0.657	1 min
Carnegie Mellon Speck (particle counts)	0.000	90%	None	1 s
Dylos DC1100 (particle counts)	0.548	95%	None	1 min
Met One 831 ($\mu g/m^3$)	0.773	90%	None	1 min
RTI MicroPEM ($\mu g/m^3$)	--	--	>0.8*	10 s
Sensaris Eco PM ($\mu g/m^3$)	0.315	100%	0.313	Unknown

* Manufacturer has developed new programming to account for this effect

Sensor Evaluation in Collaboration with NASA (Houston, TX Sept 2013)

- EPA deploying sensor technology (CairClip) for NO2 and O3 that performed well during the EPA Sensor Evaluation Open House.
- NASA deploying sensor technology (Geotech AQMesh-5) to measure O_3, NO, NO_2, CO, SO_2.
- Sampling with sensors will be used to evaluate air craft and remote measurements as well as air quality models.
- Provides EPA with additional insights and experience with the use of sensor technologies in the field for future applications.

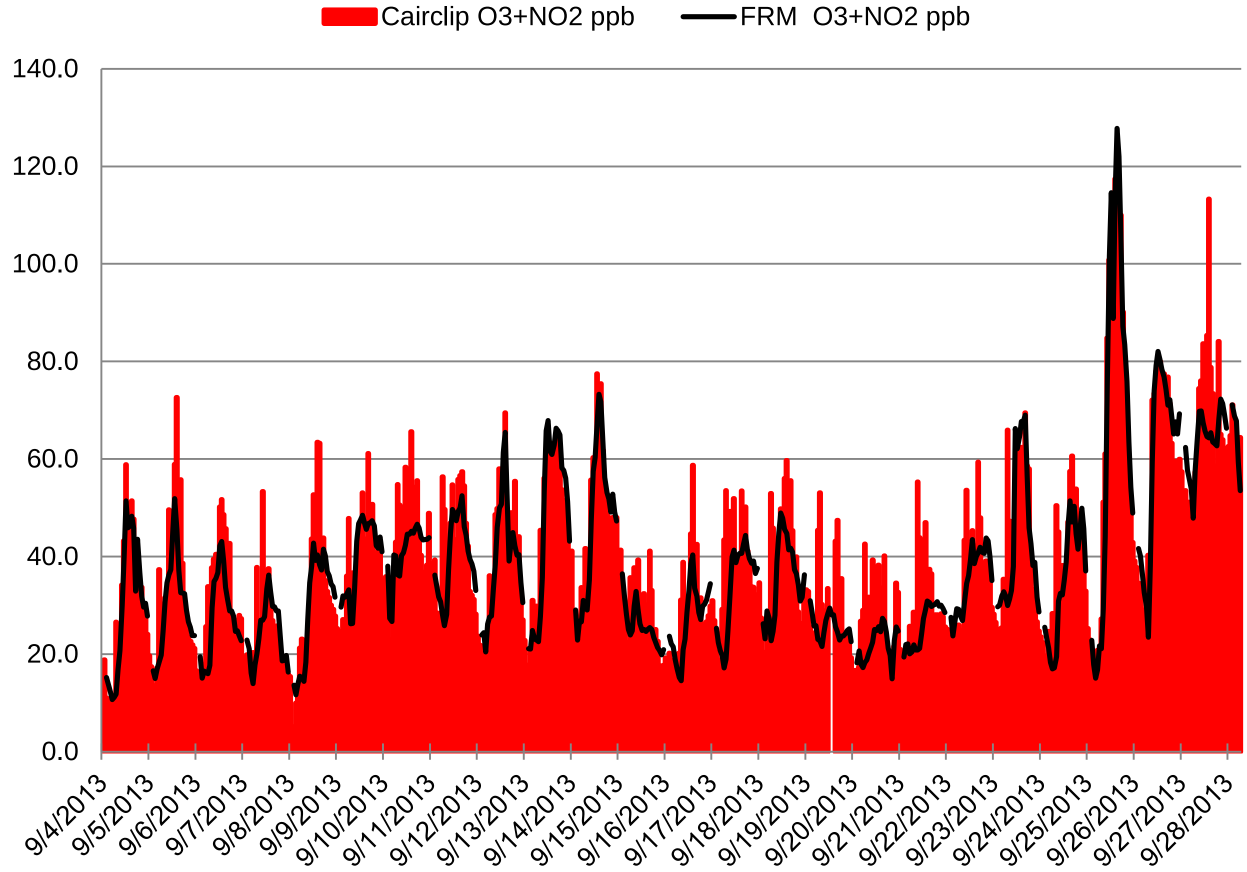
CairClip

DISCOVER-AQ Sensor Network

- Sensor network installed on August 19-20, 2013 at 8 schools
- Elementary, junior high, and high school science teachers trained on operation of sensors
- Outreach opportunities/scientist visits requested by <u>all</u> participating schools
- Teachers/students collected data with their sensor devices and incorporated sensor measurements into their lesson plans
- ORD scientists visited schools and conducted educational outreach activities

September 4-28 La Porte, TX

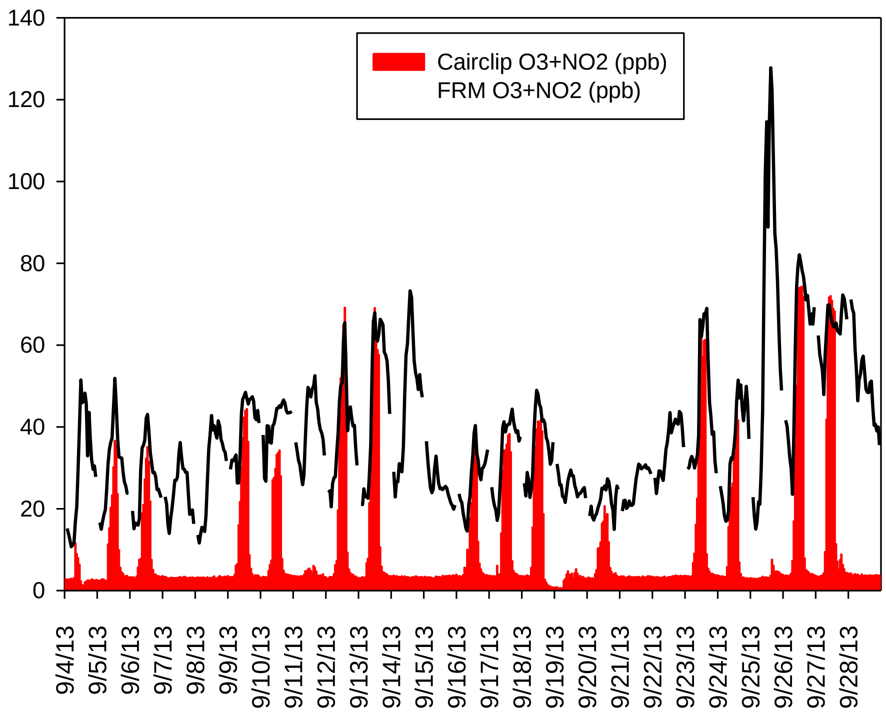
1 Hour Average

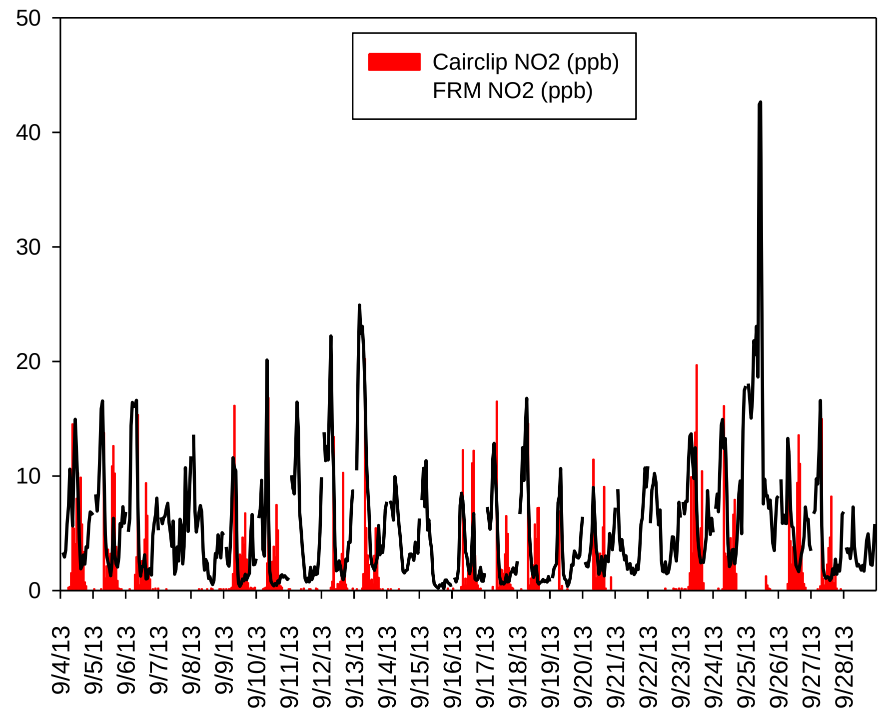


- Low cost sensors performed extremely well as compared to O_3 and NO_2 FRM' s during Houston DISCOVER-AQ field campaign
- Data from the school (citizen science) operated sensors are currently being assimilated and analyzed

Lomax Junior High-La Porte, TX
September 4-28

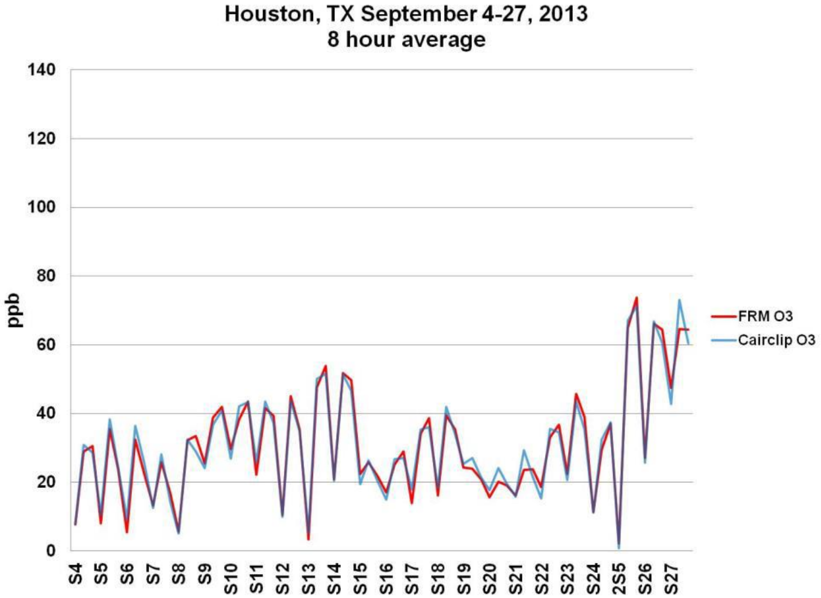
1 Hr Average

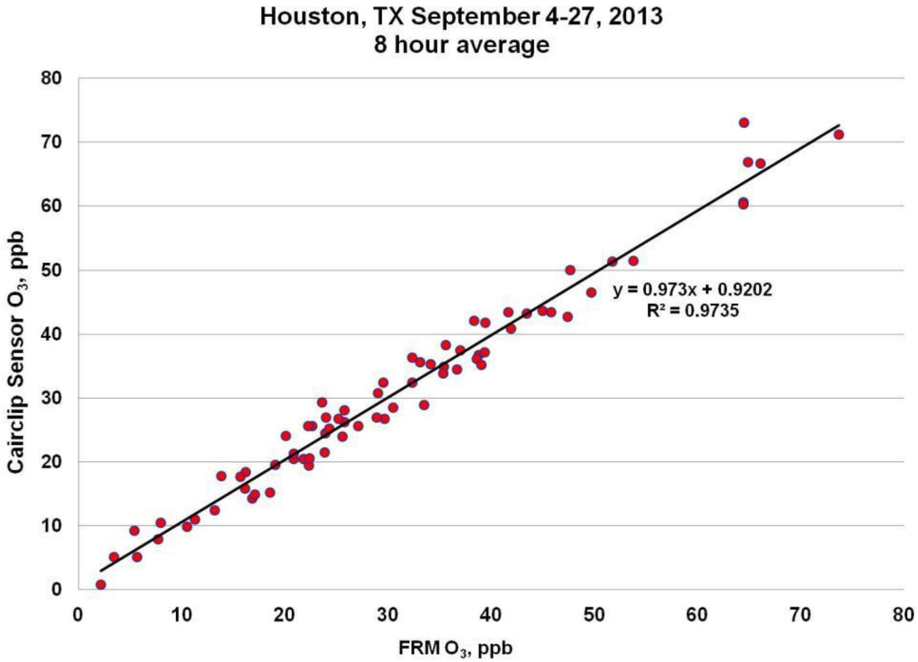




Low cost sensors performed extremely well at Lomax Junior High School. FRM O_3+NO_2 and NO_2 data collected at the La Porte Airport (~1 miles away from LJH).

DISCOVER AQ Low Cost Sensor Comparison





- Cairclip sensor data corrected by subtracting NO_2 data (as measured by NO_2 FRM) to obtain sensor O_3 results
- Sensor and FRM O_3 results averaged to 8 hours (starting at midnight) for comparison to 8 hour O_3 NAAQS
- Excellent agreement between sensor and FRM results for O_3

The Village Green Project

Solar-powered, air and meteorology monitoring bench:

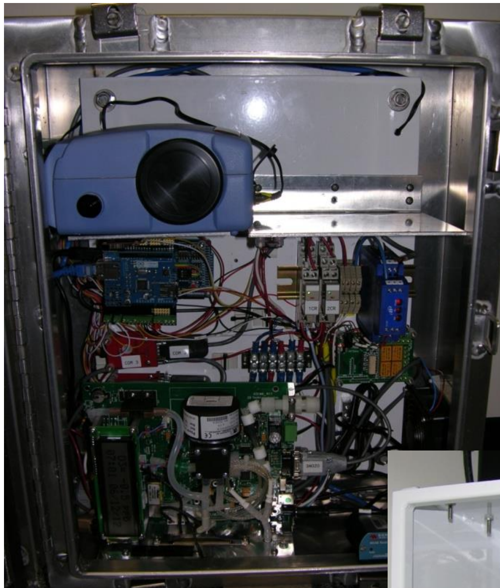
- Sustainable materials: manufactured from recycled milk jugs

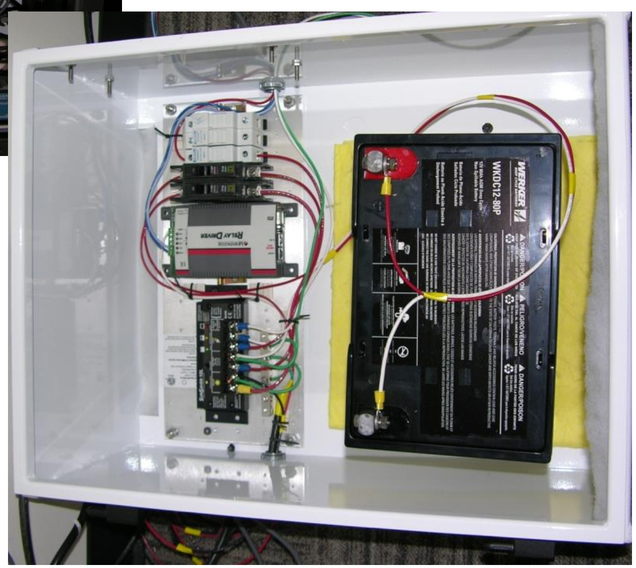
- Tamper-proof: Instruments secured in bench or base of play structure

-Designed to add value to public environments (bench)

-Formal agreement with Durham County on collaboration

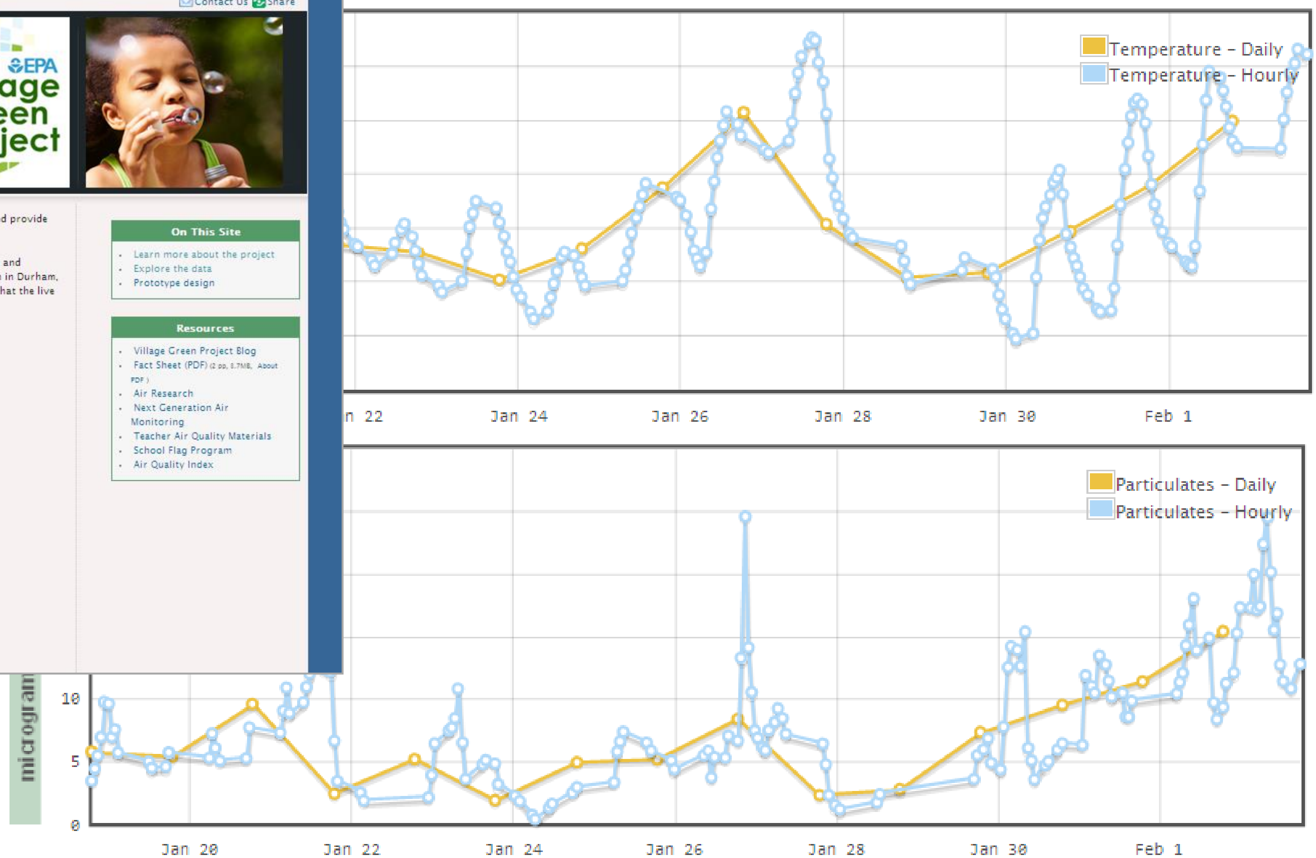
Air instruments (PM, ozone), power system and communications components stored securely behind bench





Cost of instruments, power, structure, sign ~30K

Public website updated minute-by-minute



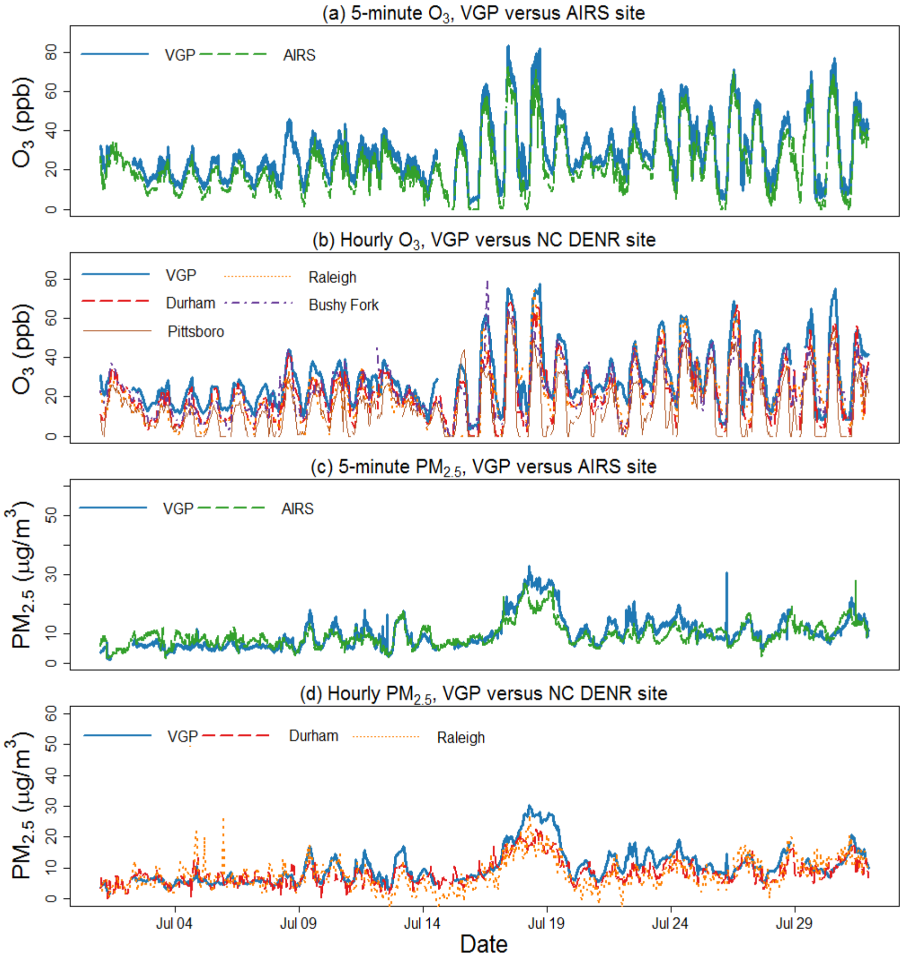
System performance

- Power system provided sufficient power for 95% operation over 10 months of data analyzed thus far (June 2013 through March 2014)

- Other causes of data collection interruption:
    - Communications – resolved initial challenges with Arduino to EPA server data transmission
    - Instrument maintenance or calibration – PM pump replacement approximately every 6 months, ozone instrument cleaning at 6 month mark

- Example typical operation for months without any instruments pulled out for cleaning or maintenance
    - During the "Arctic blast" NC winter: February completeness was 83-91% for all measured variables.
    - During hot and sunny NC summer: August completeness was 100% for all measured variables.

Comparison with nearby federal equivalent methods (FEMs)



Comparison with other sites operating FEMs in the area revealed strong agreement

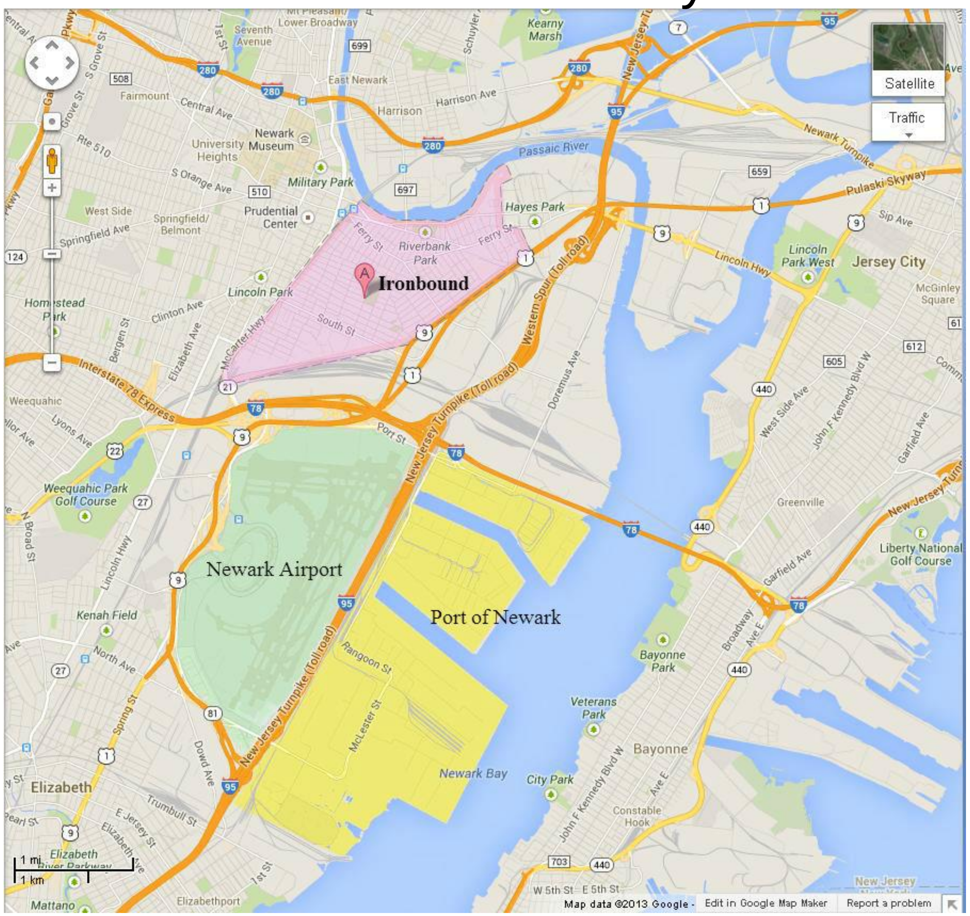
Jiao et al., in preparation

Sensor system development

Points of contact:
R2: Anhthu Hoang
ORD: Tim Barzyk, Ron Williams

Region 2 / ORD RARE Project – Citizen Science Toolkit and the Ironbound Community Corporation

Ironbound Community



Bound by:
- Highways
- Waterways
- Railroads
- Newark Airport
- Port Newark/Elizabeth

Sensor performance evaluation

Sensor system development

Points of contact:
R4: Ryan Brown, Daniel Garver
ORD: Gayle Hagler, Ron Williams

Regional Methods project: community air sensor network (CAIRSENSE)

- Long-term evaluation of low-cost sensors at regulatory site in Atlanta, GA
- Installation of 4-node multipollutant wireless sensor network surrounding the regulatory site

Key collaborators:
Region 4 – Lead
Region 5
Region 8
Region 1
OAR
ORD

Schedule / location:
- Year 1: Atlanta area installation starting in Summer 2014
- Year 2: Denver-area installation around Summer 2015

Pollutant prioritization (per Regions):
1. NAAQS
2. Air toxics
3. Other: source indicators / climate-related

Sensor system development

Region 2 / ORD RARE Project – Citizen Science Toolkit and the Ironbound Community Corporation

- Advance use of sensor technologies
- Develop a specific Tool Box for Citizen Science
- Identify pollutants of interest, appropriate sensors, deployment strategies, and data interpretation and communication methods
- Promote citizens being involved in areas associated with environmental education and awareness
- Work collaboratively with Region 2 as a test case for other Regions to consider
- Investigate feasibility of regional-led sensor loan program

Region 2 / ORD RARE Project – Citizen Science Toolkit and the Ironbound Community Corporation

Citizen Science Tool Box:

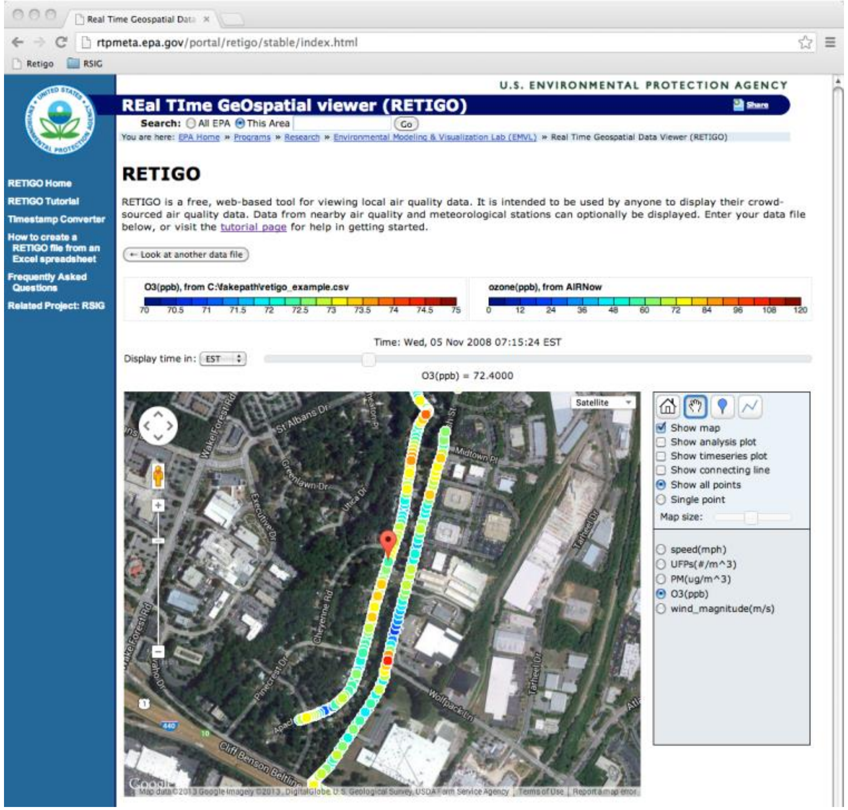
1. Basic SOP for hand-held sensors
2. One-page, quick-start guide
3. Training materials on sensor use
4. Guidance and deployment based on pollutants and sources
5. Basic ideas for data analysis, interpretation, and communication

http://www.epa.gov/research/airscience/next-generation-air-measuring.htm

Data visualization support: RETIGO

Point of contact:
ORD: Gayle Hagler

<u>Objective</u>: reduce barriers to participating in mobile air monitoring data analysis



Mobile air monitoring data:

- A function of time, location, and pollutant
- Often collected at a high time resolution (large time series)
- Variable format, location, instruments

Mobile air monitoring data analysis and exploration:

- Analysis often limited to those individuals with advanced training and access to specific software tools (e.g., MATLAB, GIS, etc.)

We are building RETIGO to support mobile air monitoring individuals and teams, reducing the technical barriers to visualize the complex data and complement advanced data analysis techniques.

What's On the Horizon

- Updated market/literature surveys.
- New PM, VOC, O_3, NO_2, SO_2 sensors being field/laboratory evaluated
- Data gathering from workshops (e.g, Air Sensors 2014; 2014 NEMC; 2014 NAAQM)
- Pursuit of new MCRADAs
- Sensor data pilot effort to integrate measurement estimates into mainstream public access (E-Enterprise)
- Expansion of Village Green deployments
- Citizen Tool Box opportunities